Theory Program Overview

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Introduction

The emphasis of the scientific research of the Nuclear Theory Program at LBNL is on the physical properties of nuclear matter under extreme conditions, from the formation of the quark-gluon plasma in high-energy heavy-ion collisions to neutron stars and to macroscopic properties of super-deformed nuclei and production of super-heavy elements. The research involves seeking theoretical understanding of properties of nuclear matter under extreme conditions from both the fundamental and effective theories of the strong interaction and developing phenomenological methods for analysis and interpretation of experimental data. Our research program has had a great impact on the phenomenological study of heavy-ion collisions. In particular, we have studied a number of possible signatures of the quark-gluon plasma, from hard QCD processes to soft pion and dilepton production and event-by-event fluctuations. We have proposed jet quenching and fluctuation of charged hadron ratios as probes of the properties of dense matter. While the majority of the group conducts research on the physics relevant to high-energy heavy-ion collisions and formation of the quark-gluon plasma, we also maintain some efforts in nuclear astrophysics and we have begun to strengthen our research in the area of low-energy nuclear physics. We also have a strong visitor program, providing connections to both theoretical and experimental activities in the division.

Initial Conditions in Heavy-ion Collisions

The main emphasis of our research program is on relativistic heavy-ion collisions and properties of the dense matter produced. One crucial question is the initial condition in high-energy heavy-ion collisions. We continued our study on the classical field-particle aspect of many body QCD, especially on how to understand the so-called McLerran-Venugopalan model of small x physics from the viewpoint of many body QCD with multiple interactions. We not only explained the main features of that model but also proposed a modification that results in some simplification and more easily extends to higher order calculations. We also studied numerically how multiple interactions reduce the gluon distribution (shadowing) inside a nucleus with various initial distributions. We propose that one can study the nuclear modification of the parton distribution via photo-production of heavy quarks in peripheral heavy-ion collisions. We also studied the effect of nuclear shadowing on initial mini-jet and transverse energy production. Our work on centrality dependence of the particle production has also stimulated a lot of interest in the subject, especially regarding whether there is any evidence of parton saturation in heavy-ion collisions at RHIC. In a slightly different direction, we plan to study higher twist parton correlations in a nucleon or nucleus via Deep Inelastic Scattering and the Drell-Yan process.

Probes of Early Dynamics in Heavy-ion Collisions

Since hard processes occur in the very early stage of the collision and their initial production rate is calculable in perturbative QCD (pQCD), they provide very good probes of the dense matter. These hard processes that we study in our group include, high pT jet and hadron production, J/ψ production and suppression, heavy quark production, direct photon and Drell-Yan production.

Our continued effort in the study of parton energy loss and jet quenching in dense matter seems to have paid off. Preliminary data from RHIC indicate strong suppression of high pT hadrons, a consequence of parton energy loss as predicted by our group. Our systematic study of high pT hadron spectra with ordinary nuclear effects has provided a baseline comparison for the experiments. We further proposed the study of azimuthal anisotropy of high pT hadron spectra as a sensitive probe of the parton energy loss that is directly related to the early parton density of the produced matter. We continue to work on multiple parton scattering and parton energy loss in both nuclear and partonic matter to achieve a deep understanding of the underlying physics especially the consequences of the deconfinement.

To provide a baseline comparison for heavy quark production in heavy-ion collisions, we have studied heavy quark production in pp collisions using pQCD up to next-to-next-to-leading order (NNLO) and to next-to-next-to-leading logarithm (NNLL) for near-threshold production. We plan to study the effects of the NLL terms on the pT and rapidity distributions of heavy quark production. We also continue to study manifestations of higher-twist effects. Using the two-component model originally developed for charm hadroproduction, we showed that higher twist intrinsic gluino contributions to final state R-hadron formation enhance leading twist production in the forward xF region.

One can also use elliptic flow measurement to study the initial evolution of the dense system, especially the initial parton thermalization. We have completed the hydrodynamical study of elliptic flow at the SPS and begun studying flow at RHIC. We were not able to reproduce the present SPS data using a hydro-dynamical model except in the most central collisions. This indicates that the collision system in non-central collisions at SPS does not achieve local thermal equilibrium. On contrast, our fit to RHIC data is excellent and indicates that thermal equilibration has taken place during the evolution of the system.

Dynamics of the Chiral Phase Transition

Following the early evolution, the quark-gluon plasma will hadronize. It is also important to study the properties of the hadronic matter, especially consequences of the chiral phase transition. On this front, continuing efforts have been made towards identifying suitable signals of the expected non-equilibrium relaxation dynamics of the chiral order parameter in high-energy collisions. Our earlier numerical simulations with the linear sigma model had suggested that the multiplicity fluctuations would be enhanced for soft pions and a recent follow-up study showed that neither HIJING nor UrQMD (in which the chiral dynamics is absent) yields such a difference between soft and hard

pions, thus supporting the specificity of this effect. It was shown that the soft pions produced by parametric amplification during the chiral relaxation process are created as back-to-back charge-conjugate pairs. Our dynamical quantum-field simulations suggest that this novel signal can be extracted from the experimental data by suitable event-by-event analysis.

In connection with these studies, further progress has been mad on real-time non-equilibrium quantum-field DCC dynamics, as an exact treatment has been developed for systems endowed with an effective function depending on both space and time. Within this framework it is particularly simple to understand the importance of the quantum fluctuations for the DCC signals.

We have also completed our study on the effect of baryonic resonances on the dilepton spectrum, which also includes prediction for the low energy run (40 GeV) at CERN. We predict no significant change of the dilepton yield per charged particle. The prediction has been confirmed by the CERES collaboration at Quark Matter 2001.

Event-by-Event Physics in Heavy ion Collisions

Due to the large number of particles produced in heavy-ion collisions at RHIC energies, event-by-event analysis of the experimental data becomes possible and can reveal physics that is otherwise difficult to study. Our work on event-by-event physics has concentrated on the fluctuations of particle ratios. The fluctuations in the ratio of charged pion yield provides a sensitive measure of the number of resonances produced at hadronization. Even more interesting, the fluctuations in the ratio of positively to negatively charged particles turns out to be a unique signature of the Quark-Gluon Plasma, since it measures the charge fluctuations per entropy. These charge fluctuations are a factor of 3 smaller in the QGP than in the hadronic phase because of the fractional charges of the quarks. At present we are working on a two-loop calculation of the charge susceptibility in a pion gas in order to see the magnitude of possible screening effects due to vector meson exchange.

As a result of our summer program we have embarked on a study of the dynamics of rare particle production and their fluctuations. Here the central question is why in heavy-ion collisions, even at low energies the kaon yield seems to be consistent with a system in chemical equilibrium. We have succeeded in deriving a master equation for the production of rare particles subject to an additional U(1) conservation law, such as strangeness. Our main finding is that the equilibration time is considerably shorter once U(1) charge conservation is properly taken into account. We have further investigated how explicit charge conservation affects the fluctuations of the system. In particular the time evolution of the second factorial moment exhibits a strong sensitivity to the degree of equilibrium reached in the system. We thus propose to measure the kaon two-particle density in these systems, which, for the first time, would provide a direct measurement of the degree of equilibration reached in a heavy ion collision.

Effective Field Theory

With the hiring of a new Divisional Fellow, we plan to expand our research program into the area of effective field theory. We plan to use effective field theory methods to solve two sets of problems in the physics of few-body systems. The first is to include electro-weak currents in a recently developed approach to three-nucleon systems at low energies. This allows for model-independent precise calculations of triton beta decay that can be used to fix the short distance contributions that are the origin of the uncertainties in neutrino-deuteron cross sections, relevant for the SNO experiment. The other involves obtaining the quark mass dependence of some low energy observables in deuteron physics. Besides its intrinsic theoretical interest, this will be instrumental in any future lattice calculation of nuclear forces. As an important off-shot of this line of research we will continue to apply the effective theory developed in the nuclear context to Bose-Einstein condensates near a Feshbach resonance, including bulk properties and three-body recombination rates.

Nuclear Astrophysics

The quark-gluon plasma we are seeking in heavy-ion collisions could also exist in the centers of neutron stars and therefore has astronomical consequences. We continued our studies of the consequences of a QCD phase transition in neutron stars, especially the crystalline structure that is expected to occur in the coexistence phase of quark and hadronic matter. We computed the varying geometrical structure and radial extent that they occupy as a function of stellar mass in two models of nuclear matter EOS. We also calculated for the first time the surface tension and curvature coefficient of a first order phase transition between two possible phases of cold nuclear matter, a normal nuclear matter phase in equilibrium with a kaon condensed phase, at densities a few times the saturation density.

We also made efforts to derive a model-independent mass-radius constraint for neutron stars that depends only on minimal and well accepted principles. Based on an analysis of radiation from Sax J1808.4-3658, which produces coherent X-ray emission with a 2.5 ms period as well as X-ray bursts, a limiting mass-radius relationship was derived which is difficult to reconcile with existing neutron star models. The derived relation would be consistent with an interpretation of Sax J1808.4 as a strange star candidate. We also explored the possibility of a third distinct family of degenerate stars at higher density than neutron stars.

We will also be involved in the study of quark matter at high baryon densities and color superconductivity and their possible consequences to neutron star physics.

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Physics of Superheavy Element Production

In the last year, we formulated the concept of shielded and unshielded fusion reactions between heavy nuclei. We found that the lowering of the Coulomb barrier shield below the relevant bombarding energy, which takes place with projectiles heavier than ^{70}Zn bombarding a 208Pb target (aimed at making elements beyond atomic number 112) correlates with the unexpectedly large cross-section for making element 118 in the unshielded reaction ^{86}Kr+^{208}Pb. We confirmed the reliability of the "Proximity potential" (underlying the calculation of the Coulomb barrier shield) by comparing its predictions with 113 measured fusion barriers. We suggested experimental tests of the unshielding hypothesis that, if confirmed, might open the way for making several new superheavy elements. We also constructed closed formulae representing the energies and fission barriers of rotating nuclei in the regime where superdeformed, triaxial "Jacobi" configurations are expected. Allowing for reduced moments of inertia at low angular momenta, associated with pairing effects, leads to modified formulae for the angular-momentum dependence of gamma ray energies, which are in approximate agreement with recent measurements at the 88" cyclotron. We also constructed a formula (based on the Thomas-Fermi model) for the isospin dependence of the nuclear surface tension.